Sea Spray Effects on Surface Heat and Moisture Fluxes

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LONG-TERM GOAL

The goal is to investigate, theoretically and through analyzing existing data, the role that sea spray plays in transferring heat and moisture across the air-sea interface, especially in high winds. Ultimately, we hope to develop simple parameterizations for these air-sea fluxes for use in large-scale models, especially those simulating tropical and extra-tropical storms.

OBJECTIVES

The ultimate goal of this work is to understand how to parameterize the air-sea fluxes of momentum and sensible and latent heat at all wind speeds. Since the COARE bulk flux parameterization (Fairall et al., 1996) is successful at winds speeds of 10 m/s or less, I focus on higher wind speeds, where sea spray is present and is a likely transfer agent. Succinctly, the first objective is to learn how to partition the air-sea fluxes between interfacial and spray contributions. The sum of the net sensible and latent heat fluxes via all routes is called the total enthalpy flux. Because it is this total enthalpy flux, rather than the individual sensible and latent heat fluxes, that provides the energy for tropical storms, the second objective is to develop a parameterization for the air-sea heat fluxes—including spray effects—that is suitable for use in large-scale air-sea interaction models.

APPROACH

This work is theoretical and analytical; there has been no experimental component. Microphysical theory establishes how rapidly spray droplets can exchange heat and moisture in a given environment. Theoretical considerations also predict how the sea spray generation function should depend on wind speed. The analytical part involves developing parameterizations for the various processes under consideration by simplifying model results or by synthesizing various data sets and observations reported in the literature. Checking the parameterizations being developed against available data is also another aspect of what I call analytical work.

Theory and microphysical modeling suggest we can estimate the total (i.e., both interfacial and spray) air-sea latent ($H_{L,T}$) and sensible ($H_{s,T}$) heat fluxes as (e.g., Andreas and DeCosmo, 1999)

$$H_{L,T} \; = \; H_L \; + \; \alpha \, Q_L \, , \tag{1}$$

$$H_{s,T} \; = \; H_s \; + \; \beta \, Q_S \; - \; (\alpha - \gamma) Q_L \, . \tag{2}$$

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Here, H_L and H_s are the so-called interfacial fluxes that I estimate with the COARE bulk flux algorithm (Fairall et al., 1996), and Q_L and Q_S are nominal spray latent and sensible heat fluxes predicted by Andreas's (1992) microphysical model. α, β, and γ are small, nonnegative coefficients obtained by tuning (1) and (2) with data.

WORK COMPLETED

To evaluate α, β, and γ, I have been using the HEXOS (for Humidity Exchange over the Sea experiment) measurements of the sensible and latent heat fluxes (DeCosmo, 1991; DeCosmo et al., 1996). The magnitudes of the nominal spray fluxes, Q_L and Q_S, in (1) and (2) depend on the sea spray generation function I use. I have tuned (1) and (2) to the HEXOS data for two candidate spray generation functions—Andreas (1992) and Andreas (1998). With the former, $\alpha = 4.3$, $\beta = 6.5$, and $\gamma = 3.8$; with the latter, $\alpha = 9.8$, $\beta = 15.0$, and $\gamma = 9.3$. The differences in these values reflect the persistent uncertainty in the magnitude and wind speed dependence of the spray generation function.

Because the Andreas (1998) spray generation function treats 10-m wind speeds, U_{10}, up to 32.5 m/s while the Andreas (1992) function is appropriate only up to 20 m/s, I have been concentrating recently on parameterizations based on the Andreas (1998) function. This allows me to treat air-sea heat fluxes in winds of almost hurricane strength.

In collaboration with Kerry Emanuel at MIT, this year I investigated what my spray model says about the net air-sea enthalpy flux. From (1) and (2), that net enthalpy flux is

$$Q_{e,net} \;=\; H_{s,T} + H_{L,T} \;=\; (H_s + H_L) + (\beta\,Q_S + \gamma\,Q_L). \tag{3}$$

The first two terms on the right-hand side of (3) give the interfacial enthalpy flux,

$$Q_{e,int} \;=\; H_s + H_L, \tag{4}$$

which is modeled fairly well with a bulk-aerodynamic formulation, such as the COARE algorithm (Fairall et al., 1996). The last two terms in (3) give the enthalpy flux associated with spray processes,

$$Q_{e,sp} \;=\; \beta\,Q_S + \gamma\,Q_L. \tag{5}$$

Note that the terms in (5) derive strictly from the sensible heat exchange, as modeled by (2). Few have recognized this fact and, thus, have generally ignored this important route for air-sea enthalpy exchange. Consequently, no large-scale air-sea interaction model is currently parameterizing the spray contribution to the air-sea heat flux with the proper physical basis. Recently, however, Andreas and Emanuel (1999) have begun incorporating spray effects in Emanuel's (1986, 1995) axis-symmetric tropical cyclone model, using (5) as a guide. We presented our preliminary work at the Annual Meeting of the American Meteorological Society in January 1999 and have, more recently, been developing a journal article based on this research.
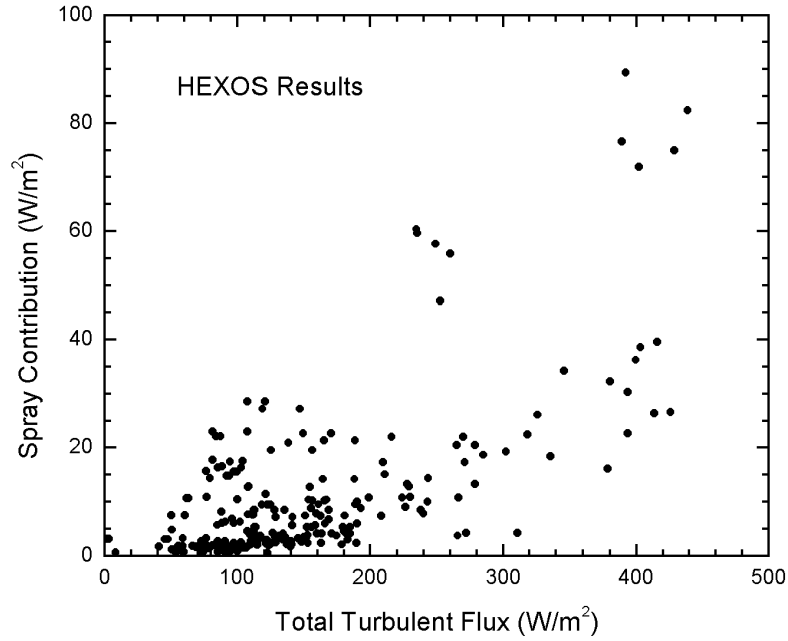
Figure 1. HEXOS results demonstrating the contribution that spray makes to the air-sea enthalpy flux versus HEXOS measurements of the total enthalpy flux (i.e., $H_{s,T} + H_{L,T}$). The results are based on the Andreas (1998) spray generation function.

RESULTS

Figure 1 shows what the HEXOS data say about the contribution that sea spray makes to the air-sea enthalpy flux. This figure shows the spray enthalpy flux, as modeled by (5), versus values of the total air-sea enthalpy flux, $H_{s,T} + H_{L,T}$, measured during HEXOS (DeCosmo, 1991). As the total turbulent (enthalpy) flux increases—which generally means increasing wind speed—the spray contribution remains, typically, about 10% of the total. Ten points, however, show spray contributions of 20-30% of the total flux. Since the maximum 10-m wind speed represented in this data set is only 18 m/s, we can infer that, in storm winds, the spray contribution will, indeed, be important.

With Kerry Emanuel, I have been developing a parameterization for $Q_{e,sp}$ that is simple enough to use in large-scale air-sea interaction models. Our current provisional parameterization is

$$Q_{e,sp} = \rho_w \, c_w \, (T_s - T_{eq}) \, f(U_{10}) . \qquad (6)$$

Here, ρ_w is the density of seawater; c_w, the specific heat of seawater; T_s, the sea surface temperature; and T_{eq}, the equilibrium temperature of spray droplets with a radius of 100 μm at formation (Andreas, 1995, 1996). Finally, $f(U_{10})$ is a function of the 10-m wind speed that predicts the total mass flux of spray droplets at the sea surface. We are currently basing this function on the HEXOS data and the wind dependence implicit in the Andreas (1998) spray generation function.

IMPACT

In finding that sea spray can accomplish a net enthalpy exchange across the air-sea interface, we have identified an unappreciated source of energy that can influence the intensity of tropical and extra-

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tropical storms. Fairall et al (1994) were the first to investigate how sea spray could affect the development of the marine boundary layer in a tropical cyclone and confirmed that the spray does redistribute heat between the temperature and humidity fields. By identifying how and how much the spray can affect the net air-sea enthalpy flux, we have shown that, not only does the spray redistribute heat in the atmosphere, it can actually transfer energy across the air-sea interface and therefore affect storm intensity. Andreas and Emanuel (1999) incorporated these ideas, in preliminary fashion, into Emanuel's (1996, 1995) tropical cyclone model and demonstrated that the heat carried by spray can have profound effects on the maximum wind speed in tropical cyclones.

The effect of spray on ocean storms is a fairly hot topic because, although current air-sea interaction models provide fairly good predictions of the storm track, they do poorly in predicting storm intensity. Consequently, since that Andreas-Emanuel (1999) proceedings paper identified an unrecognized source of heat for the storm, I have received requests for advice and computer code and invitations to collaborate on spray modeling from several scientists working in this area.

TRANSITIONS

Although I have been answering requests for advice on sea spray processes, the most direct transition of this research is through my collaboration with Kerry Emanuel. We are parameterizing the results of my modeling and analysis for use in Emanuel's tropical cyclone model to investigate what role spray plays in setting the intensity (i.e., the maximum wind speed) of tropical storms. The obvious goal of this work is to better forecast hurricanes.

I have also contributed to the recent ONR "whitepaper" that describes an initiative for comprehensive research on coupled air and sea boundary layers. In particular, I contributed to sections on sea spray processes and issues in high winds, where we have little observational basis for understanding air-sea transfer.

RELATED PROJECTS

There are no other funded spray projects at CRREL. I have, however, managed to modestly leverage my ONR funding with my base CRREL funding. This, for example, provides overhead support for secretaries, computer specialists, library staff, publications charges, and for miscellaneous supplies. In the past year, I have also leveraged my ONR funds by collaborating on this spray research with Janice DeCosmo at the University of Washington, Ed Monahan at the University of Connecticut, and Kerry Emanuel at MIT, who are funded under projects at their own institutions.

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